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Thermal aging effects on microstructures and mechanical properties of an environmentally friendly eutectic tin-copper solder alloy

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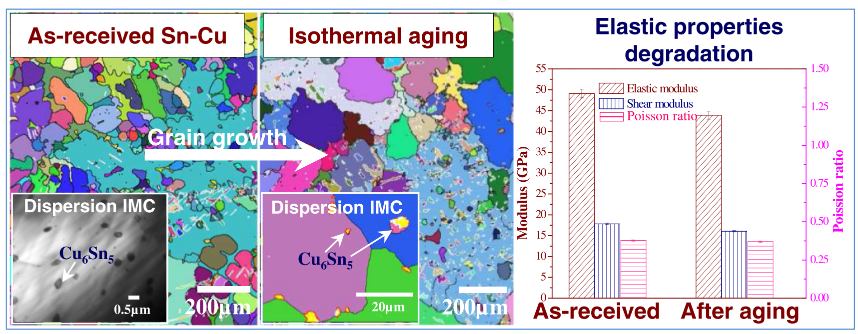
HIGHLIGHTS

- Evaluation of mechanical properties of a tin-copper solder alloy is conducted for finding an environmental friendly electronic packaging material.
- Prior aging there is a mix of coarse and fine intermetallic dispersions that coarsen preferentially at grain boundaries.
- Particle coarsening has adverse effects on the overall mechanical performance and an inferior device life span is speculated.

GRAPHICAL ABSTRACT



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ABSTRACT

This paper describes the changes in microstructures and their effects on property degradations in an environmentally friendly eutectic Sn—0.7Cu (wt.%) solder alloy when subjected to harsh service conditions. A thorough microscopy investigation was conducted by scanning electron microscopy (SEM), electron backscattered diffraction (EBSD) and diffraction analysis with transmission electron microscopy (TEM). In the as-received alloy Cu_6Sn_5 intermetallic compound (IMC) particles are dispersed in the grain interiors and grain boundaries of β-Sn matrix. When the alloy was exposed for 60 days at 150 °C, the size of Cu_6Sn_5 IMC particles and Sn matrix grains were increased significantly. As a result the mechanical reliability of electronic interconnections turned inferior. This was confirmed by measuring a range of electrical and mechanical properties that include electrical resistivity, Young's moduli, shear moduli, microhardness and nano indentation creep behaviour. A comparison between the as-received and age-treated alloy shows that the degradation in Young's and shear moduli was about 10.6 and 9.9%, respectively, and that in hardness was about 25%. However the age treatment improved the damping property of the alloy.

1. Introduction

Electronic interconnects serve both electronic and mechanical functions between the electronic components (transistor, chips, integrated circuit etc.) and printed circuit boards (PCBs) in electronic devices [1, 2]. There have been extensive investigations on the development of environmentally friendly Sn-based alloys in the last two decades. The

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primary aim is to develop environmentally friendly electronic interconnect materials to replace the traditional Sn—Pb solder, which have been recognized toxic to the device users [2–5]. Among many lead-free Sn-based interconnect alloys the eutectic or near eutectic Sn—Cu solders have been recognized as promising candidates in the electronic packaging industries for having a combination of commercial and technical advantages such as low processing cost, moderate melting temperature (227 °C), good anti-oxidation properties, lower reactivity with Cu which is a commonly used substrate material [6–8]. In addition, the formation of Cu_6Sn_5 and Cu_3Sn intermetallic (IMC) particles provides improved thermal cyclic fatigue and wetting properties in these alloy grades [8]. However, it has been reported that the mechanical properties of the lead-free solder alloys varies with temperature [9,10]. This poses challenges in wide spread usages of this material since in some service applications there are possibilities of temperature increments. Temperature variations in solder materials may arise due to two principal reasons: downsizing interconnect bumps in flip-chip technology in miniaturized electronic devices and harsh service conditions [11,12].

A typical interconnect bump of electronic packaging carries a current in 0.2–0.4 A range, which produces a current density in 2×10^3–2×10^4 A/cm^2 range [13]. However, in miniaturized electronic devices the diameter of interconnect bumps in flip-chip technology is expected to be reduced from the present dimension of 100 μm to 1 μm in near future. Thus, the interconnect material volume would be reduced by six orders of magnitude and therefore the current density would increase up to 1×10^6 A/cm^2 [14]. Further, the size reductions result large temperature gradients, which could be as high as 3000 °C/cm [15], which is at least three times larger than that in the conventional bulk bumps [16]. Higher temperature gradient also degrades the mechanical properties through causing migration-induced failures in the packaging systems. Moreover, the growth behaviour of the intermetallic compound phase through the solid-state aging is of particular interest to the electronic packaging industries [17]. In earlier studies, several research groups aimed to fabricate electronic interconnections on different surface-finished Cu substrates using reflow process. Further, the electronic interconnections are aged isothermally (at about 150 °C) with varying time (500–1500 h) to evaluate the morphology, growth kinetics of interfacial IMC layers and shear strength of interconnections [17–20]. These conditions are adopted because of two board reasons: (i) IMC formations get facilitated at these conditions [18] and (ii) industrially these conditions are adopted for simulating harsh service applications. Therefore, our current understanding on growth behaviour of IMC particles in solder matrix and their effects on mechanical properties after isothermally aging (at 150 °C for 60 days) when incorporated in lead-free eutectic Sn—Cu bulk solder alloys are limited. The present study aims to evaluate the mechanical reliability (i.e., hardness, Young's moduli, creep and fatigue behaviour etc.) of the newly developed lead-free solder alloys after conducting aging at 150 °C, and correlate the properties with microscopy and thus estimate mechanical integrity of the devices during equivalent operating conditions.

Examples of harsh service condition may include thermal fluctuations, cyclic strain/stress, vibration and mechanical shock. Thermal fluctuations commonly arise by switching on/off of the device. This in turn also influences the elastic behaviour and creep properties. Solders materials are particularly vulnerable to creep, even at ambient temperatures, since the room temperature is above half of the homologous melting point of the alloys [21,22]. Moreover, the contemporary electronic products are frequently subjected to different form of vibrations and this has detrimental effects on the sustainability of the solder interconnects [23–25]. Therefore it is important to evaluate the ability to dissipate energy during vibration, and this is measured by the so called 'damping capacity'. In the existing literature it is demonstrated that materials with high damping capacity are suitable for a wide range of engineering applications, because in recent times the vibration and noise reductions vary over wide ranges in various applications [26]. Therefore it is a fundamental scientific interest to correlate the microstructure and properties (temperature dependence Young's moduli, electrical performance, damping capacity, creep behaviour and hardness) of Sn—Cu solders when subjected to harsh service conditions.

The present study aims finding the degradation behaviour of the eutectic Sn—0.7Cu solder alloys when subjected at 150 °C temperature for varying time. Therefore the specific goals are to: (a) elucidate the microstructures in the as-received and aging conditions, (b) evaluate the mechanical and electrical properties at various operating temperatures, (c) evaluate the creep performance and (d) measure the strain amplitude dependent damping properties.

2. Experimental procedure

2.1. Material and characterization

A lead-free eutectic Sn—0.7Cu (wt.%) solder alloy was obtained in as-cast condition from , China. The material was cut into cuboid sections of 40.0 mm × 7 mm × 2.2 mm dimensions by a wire cutting machine under the cooling action of Dx-1 coolant from Cosmos Machinery International Ltd. to avoid the artefacts from heat that generates during cutting. The samples were then ground by different grit size emery papers and finally polished with Al_2O_3 suspension to obtain polished samples of approximately 40.0 mm × 6.8 mm × 1.8 mm dimensions. Then the samples were placed into a high-temperature oven at 150 °C with a temperature variation of ±2 °C for 60 days. Finally both the as-received and heat-exposed samples were studied using a Hitachi S3400 scanning electron microscope (SEM) and Oxford electron back-scattered diffraction (EBSD) detector attached with a Carl Zeiss Auriga field emission gun (FEG) SEM for obtaining structural and crystallographic information, respectively. EBSD data was analysed by Channel 5™ software. For preparing EBSD samples the mechanically polished samples were ion milled by a wide angle 3.5 kV beam in a Hitachi IM4000 ion milling machine. For preparing electron transparent thin samples for transmission electron microscopy (TEM) investigations the mechanically thinning step was limited to ~300 μm thickness due to reduced hardness of the material. Then the samples were thinned by a 3 kV argon ion beam in a Gatan PIPs machine until it produces a hole near the middle of the 3 mm disk. TEM characterization was conducted by a Philips CM200 FEG TEM machine operates at 200 kV beam energy.

2.2. Property evaluations

The elastic properties of the as-received and heat-exposed specimens, including Young's modulus (E), shear modulus (G) and Poisson's ratio (ν), were measured by IMCE machine (IMCE RFDA HT 1050) according to impulse excitation technique. Briefly on this technique, the sample of a dimension of 38.68 mm × 6.8 mm × 1.8 mm was suspended by thin metal wires in the machine chamber and impacted by a ceramic bar. Then the emitted flexural and torsion vibration signals of the specimens were collected by a microphone and analysed by Fast Fourier transform. Then the Young's modulus and shear modulus were derived from the flexural and torsion vibration frequencies, respectively, according to the ASTM (American Society for Testing and Materials) standards [27,28]. In addition, Poisson's ratio also determined according to $\nu = (E/2G) - 1$. Ten such impact tests were conducted on each sample for obtaining an acceptable average. The Young's moduli degradation behaviour was evaluated from room temperature to 180 °C (~0.91 T_m) range in an inert atmosphere of argon. The room temperature average microhardness with a series pattern of nine points was measured by a Vickers hardness tester (DuraScan, Struers, made by Emco-Test) of two samples with an applied load of 0.3 kg and 5 s dwelling time. To evaluate nano-indentation based creep properties a constant-load of 2 mN was applied for 120 s with a series pattern of five points of three samples using a Hysiron TI-950 Tribo Indenter nano-indentation system. The electrical resistivity was measured in 25 to 100 °C temperature range using a precision LCR meter (Agilent E4980A 20 Hz to 2 MHz). The